2.4 Acoustics

Christopher S. Allen

Chairman, ISS Acoustics Working Group and Orion Acoustics Working Group

ISS Acoustics System Manager, Orion Acoustics System Manager

Co-chair, ISS Multilateral Medical Operations Panel Acoustics Sub-working-group

Lead, Johnson Space Center Acoustics Office

Johnson Space Center

National Aeronautics and Space Administration

Houston, Texas, USA

Based on earlier edition written by:

Jerry R. Goodman

Chairman (Former), Acoustics Working Group and ISS Acoustics Lead, retired

Ferdinand W. Grosveld, D.E.

Consultant, Hampton, Virginia, USA

2.4.1 Acoustics safety issues

The acoustics environment in space operations is important to maintain at manageable levels so that the crew can remain safe, functional, effective, and reasonably comfortable. High acoustic levels can produce temporary or permanent hearing loss, or cause other physiological symptoms, such as auditory pain, headaches, discomfort, strain in the vocal cords, or fatigue.

Noise is defined as undesirable sound. Excessive noise can result in psychological effects, such as irritability, inability to concentrate, decrease in productivity, annoyance, errors in judgment, and distraction. A noisy environment also can result in the inability to sleep or sleep well. Elevated noise levels can affect the ability to communicate, understand what is being said, hear what is going on in the environment, degrade crew performance and operations, and create habitability concerns. Superfluous noise emissions also can create the inability to hear alarms or other important auditory cues, such as the sound of an equipment malfunction. Recent spaceflight experience, evaluation of the requirements in crew habitable areas, and lessons learned (Allen *et al*. 2003, Goodman 2003, Grosveld *et al*. 2003, Pilkinton 2003) show the importance of maintaining an acceptable acoustics environment. This is best accomplished by having a high quality set of limits and requirements early in the program, *i.e.*, the designing-in of acoustics in the development of hardware and systems, and by monitoring, testing, and verifying sound levels to ensure that they are acceptable.

2.4.2 Acoustic requirements

Requirements are a key pillar to successful design, and need to be as well defined and as clear as possible at the beginning of a program. To be successful in meeting the requirements, acoustics needs to be treated as a technical specialization on par with other design disciplines, and experienced and knowledgeable personnel need to be assigned to implement the defined requirements. The following factors should be considered when tailoring requirements to meet a specific application:

- Type of mission;
- Mission duration;
- Number and characteristics of crew occupants;
- Size, function, number, and type of hardware systems that make up the crewed vehicle, module, or enclosure, and the supplementary hardware such as payloads and supplementary government furnished equipment;
- Whether single or dual shift operations is to be used;
- Distance between crewmembers that is required for good communications; and
- Quality of the communications needed.

All requirements presented in this chapter apply throughout the crew habitable volume. Separate acoustic restrictions need to be applied to areas that are outside of this habitable volume, but which have the capability to be accessed for short-term use for equipment change out or for maintenance. Special consideration should be given to the acoustic levels allowed in the habitable volume should such access require leaving open access doors, panels, or other means for sound to enter. The terms applied to the habitable volume in a crewed spacecraft, module, or other types of

crewed enclosures used in space are the crew compartment, habitable volume, or the habitat. Use of design goals in lieu of firm requirements is not recommended, because they set the stage for efforts that are essentially “do what you can do”, and imply that efforts should be limited to those objectives that readily can be met, or that can be interpreted thusly. Some important acoustic safety requirements currently employed by NASA and its International Partners in manned spacecraft applications are discussed in the following sections.

2.4.2.1 Continuous noise

Spaceflight missions typically range in duration from several days to many months, and will extend to multiple years for missions to Mars. Special requirements are needed to administer the twenty-four hours per day, seven days per week exposure to noise in space vehicle environments safely. Noise sources operating for more than eight hours in any twenty-four hour period are classified as those producing continuous noise. In 1972, NASA adopted noise criteria or NC curves as the acoustic noise criteria standard used to manage continuous noise in manned spacecraft (NASA 1972). The NC curves specify the octave band limits of the acceptable noise levels in habitable environments while all systems are operating. As well, they commonly are used in industry for defining the ratings used for control of ambient noise in buildings. The acoustic environment, with the integrated government furnished equipment as part of the habitable space, is limited by the NC-50 curve shown in Figure 2.4.2.1-1. These curves are extrapolated to include the 16 kHz octave band to cover better the audible range at the higher frequencies.

[Figure 2.4.2.1-1 here]

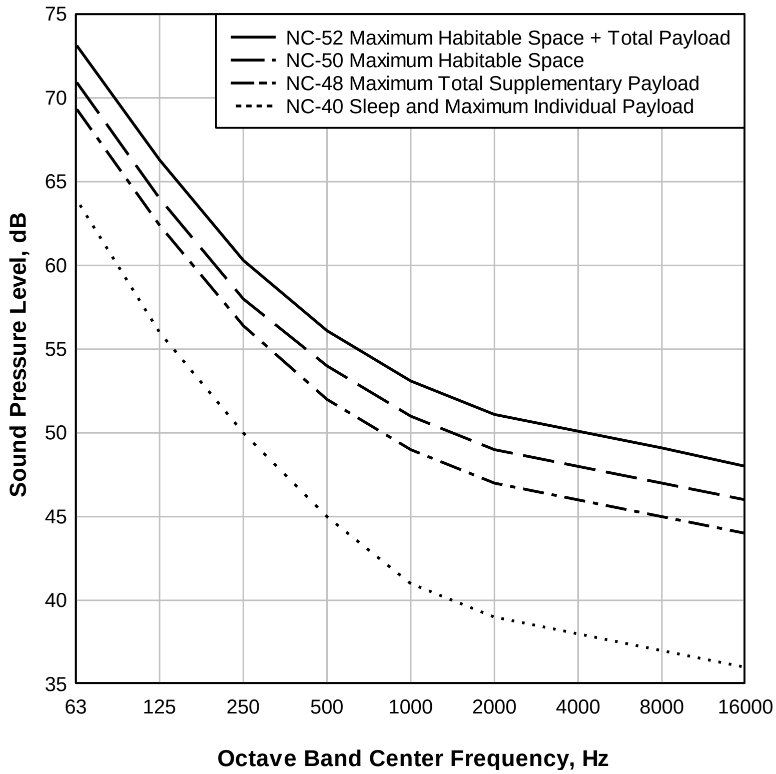

Figure 2.4.2.1-1: Extended continuous noise criteria specifications.

An appropriate limit or allocation can be developed and applied to the complement of other noteworthy hardware located within the crew compartment or habitat that is not required for the basic functioning of the spacecraft, module, or enclosure systems. In the past, this category included such items as payloads, non-integrated equipment, experiments, cargo, or other classifications of hardware. If these payloads and other types of hardware, together, amount to a considerable acoustics contribution as have the payload racks in the International Space Station, then an allocation for them as a complement can be made, and is then limited to NC-48 in consonance with the limits applied to the integrated system and crew compartment or habitat (NASA 2003). Each individual rack equivalent item should meet the NC-40 curve per Figure 2.4.2.1-1, or lower, as an applicable suballocation (NASA 2000a). Appropriate suballocations also need to be given to hardware components that make up payload rack type hardware to ensure

that the rack limit is controlled. This is especially true if rack makeup or components are changed out during the operational life of the rack or hardware. An individual hardware item that is of lower complexity than a payload rack, and that is similar to an item of hardware mounted in the aisle should either fit into the complement total limit, or meet a lower limit itself. The continuous acoustic levels for the integrated systems affecting the crew compartment or habitat, including the noise from supplementary hardware, *e.g.*, payloads, non-integrated government furnished equipment, or other classifications, is then limited to the NC-50 + NC-48, or NC~52, which is an approximate NC-52 level, shown in Figure 2.4.2.1-1. Sound levels of NC~52 are 1 dB greater than the standard NC-52 curve in the 63 Hz and 125 Hz octave frequency bands. An alternative approach is to control the total composite noise level of the systems and complement of payloads or other equipment to the approximate NC~52 curve. This allows unused system hardware allocation to be used by the payload complement, for example, or vise-versa. In this case end-items such as racks, subracks, and portable equipment should still have a suballocated requirement to meet, e.g. NC-40 for payload racks. However, If the supplementary hardware system is considerably less complex in nature than the International Space Station payload rack hardware, and it does not merit the NC-48 level allotment, the total noise in the crew compartment or habitat should be controlled to the NC-50 rather than the NC~52 level. The NC-50 specification, which is preferred over the NC~52 level because it provides for improved quality of communications and word intelligibility, is recommended for crewed spacecraft in general, *e.g.*, the Space Shuttle and the International Space Station (NASA 1972, Pearsons 1975, Piland 1980, CHABA 1987). Figure 2.4.2.1-2 shows the quality of face-to-face communications expected for vocal effort and separation distance in terms of speech interference level, using the four-band method, SIL(4), and dBA levels (ANSI 2006.

[Figure 2.4.2.1-2 here]

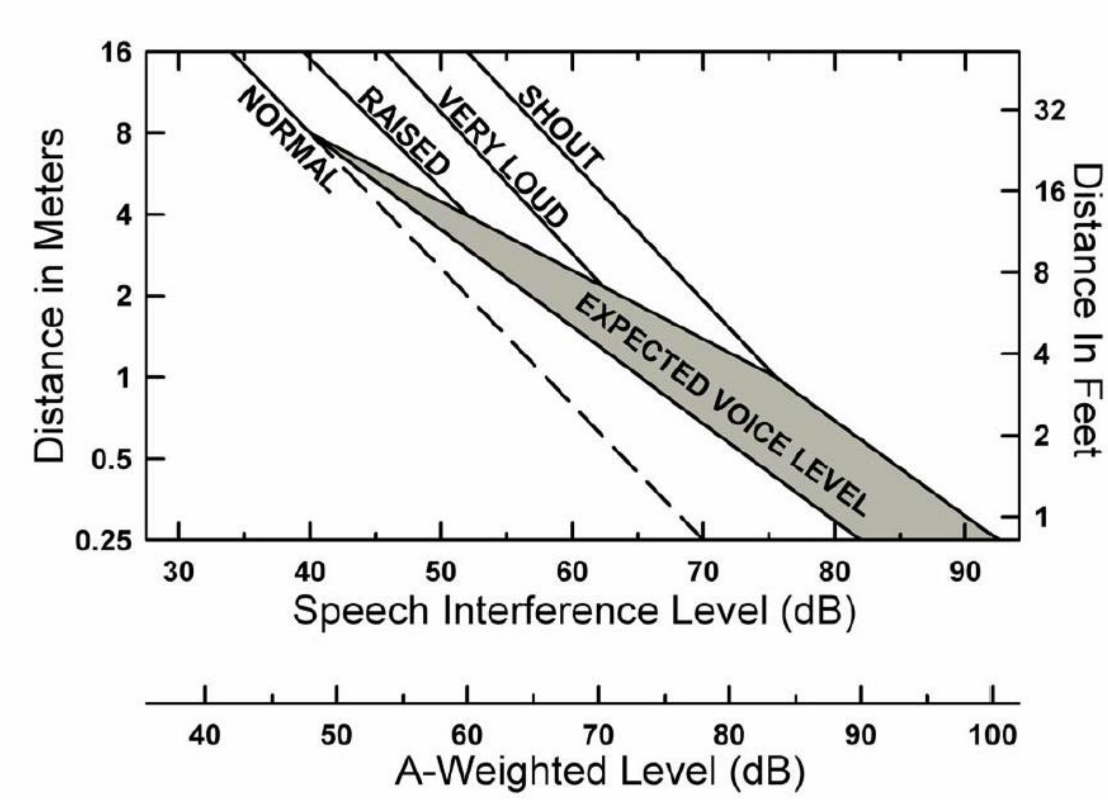

Figure 2.4.2.1-2: Talker-to-listener distances for just-reliable face-to-face communication. Effectiveness of voice communications as function of the speech interference level, SIL(4), or the dBA noise level and the distance from speaker to listener.

The speech interference level, four band method, was established to determine the effect of continuous background noise on speech communications in a work environment. It is defined as the arithmetic average of the sound pressure levels in the 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz octave bands. Figure 2.4.2.1-2 also shows the same evaluation against an A-weighted background sound level. Just-reliable face-to-face communications is defined as 70% intelligibility for monosyllabic words (ANSI 2006). Figure 2.4.2.1-3 shows the percent intelligibility levels plotted *versus* the NC ratings (or dBA levels) for crew-to-crew communication distances from five feet to eight feet. Improvement in intelligibility is shown by

the use of NC-50 *versus* the NC-52 rating (Pearsons 1975). The minimum percentage of intelligibility is recommended by NASA to be 75% for the satisfactory communication of most messages (Figure 2.4.2.1-3). An intelligibility of 95% is recommended for sentences spoken under normal vocal effort with the talker and listener being visible to each other (CHABA 1987). Note that the data used for this curve is based on communications between males conversing in the English language, and does not take female voices or foreign dialects into account.

[Figure 2.4.2.1-3 here]

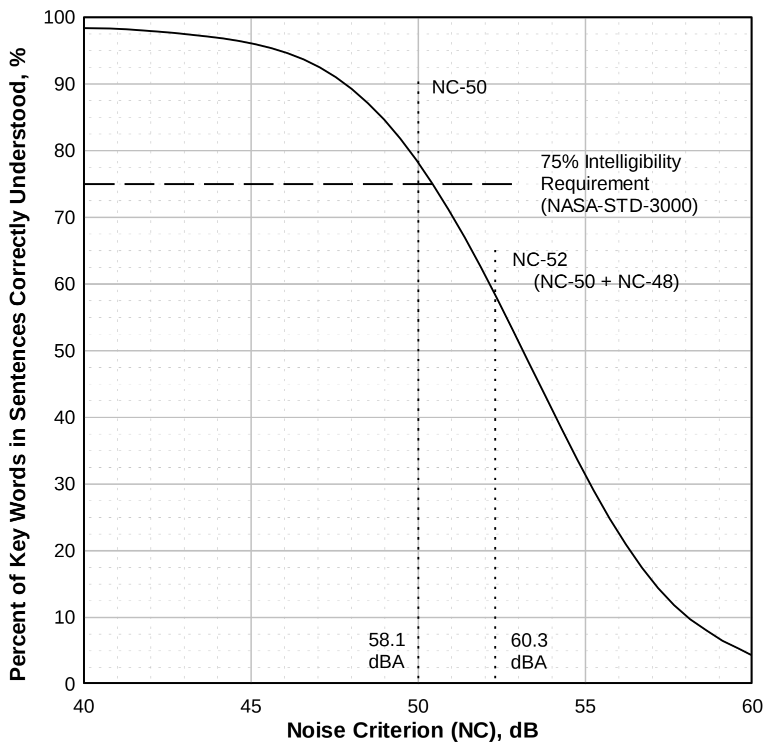

Figure 2.4.2.1-3: Percent intelligibility level *versus* the noise criteria rating for crew-to-crew communication at distances from five feet to eight feet.

The crew needs a reasonable limit for the acoustic levels present during their sleep periods so that they can obtain necessary rest and recover from any high noise exposure during their activity

periods. Where the crew compartment or habitat design permits, the sleeping area should be an accommodation that is separated from areas of work and the higher noise. The crew sleeping area should not exceed NC-40, as shown in Figure 2.4.2.1-1 (NASA 1972, NASA 1995). To preclude any awakening of sleeping crewmembers, impulse or transient noises in the sleeping area should be limited to less than 10 dB above the background noise (NASA 1972, NASA 1995).

2.4.2.2 Intermittent noise

Intermittently, *i.e.*, eight hours or less in any twenty-four hour period, operating hardware can be very disturbing, wake crewmembers, and interfere with sleep or nominal operations. Supplementary hardware, such as that found in the payload rack classification, should limit intermittent A-weighted acoustic emissions to the levels and durations defined in Table 2.4.2.2-1 with measurements taken 0.6 m from the loudest point on the hardware (NASA 2000a).

Table 2.4.2.2-1: Intermittent A-weighted overall sound pressure levels and corresponding operational limits for supplementary hardware, *e.g.*, rack mounted payload hardware and non-integrated government furnished equipment.

Maximum Noise Duration (per 24-hours)	A-weighted Overall Sound Pressure Level [dBA]
8 Hours	49
7 Hours	50
6 Hours	51
5 Hours	52
4.5 Hours	53
4 Hours	54
3.5 Hours	55
3 Hours	57

2.5 Hours	58
2 Hours	60
1.5 Hours	62
1 Hours	65
30 Minutes	69
15 Minutes	72
5 Minutes	76
2 Minutes	78
1 Minute	79
Not Allowed	80

It is recommended, when the noise duration is 1 hour or shorter during a 24-hour period, that the intermittent noise requirement only apply to those noise sources that are crew-activated or only occur 3 or less times per 24-hour period. A noise source with sound level of 72 dBA that operates for just a few seconds at a time, but repeats itself every 30 minutes, could be very annoying in a 58 dBA background noise environment. Some crew compartment hardware, such as toilets, pressurized gas systems, or other stand-alone hardware of acoustic importance should be controlled similarly. Most exercise equipment, *e.g.*, treadmills and ergometers, can be difficult to control to these limits, and depending upon crew size, *et cetera*, they can produce loud acoustic levels over time. It is suggested that, if possible, the exercise area be allotted separate quarters from other habitable areas in the crew compartment or habitat.

2.4.2.3 Narrow band components

A narrow band component is a simple or complex tone, or a line spectrum having intense and steady state frequency components in a very narrow band, *i.e.*, 1% of an octave band or 5 Hz, whichever is less, and is heard as a musical note or sound, either harmonic or discordant. The maximum sound pressure level of any narrow band component should be at least 10 dB less than

the sound pressure level of the octave band that contains the component (NASA 1972, NASA 1995).

2.4.2.4 Ultrasound and infrasound

Ultrasound is high frequency sound, *i.e.*, above 15 kHz to 20 kHz, that is inaudible to the human ear. Ultrasonic sound can have physiological effects on humans, and it should be addressed as part of the acoustic environment. It is thought, however, that pertinent concerns regarding ultrasound should be focused on direct body contact and any audible noise associated with the subharmonics of the hardware that produces it. Ultrasonic noise can be generated by electrical converters, battery chargers and other types of equipment. There are two concerns of importance when dealing with this type of noise:

- It is difficult and costly to predict whether the hardware produces levels in the crew compartment or habitat that are sufficient to be of concern or that exceed defined limits; and
- The hardware and techniques required to measure ultrasonic emissions are expensive and involved, and so are commonly not available or used.

Use of the extended noise criteria curves to 16 kHz (Figure 2.4.2.1-1) helps to understand and control most subharmonic effects in the audible range, but it is recommended that some screening be used to determine if the resultant ultrasonic levels in the crew compartment or habitat are of concern or exceeds any recommended threshold limit value as shown in Table 2.4.2.4-1 (ACGIH 2004). High ultrasonic noise also can interfere with systems designed to detect micrometeoroid impacts and resulting holes or leaks, and can also be an issue for science experiments involving rodents or other animals.

Table 2.4.2.4-1: Threshold limit value for ultrasonic sound in air.

One-third Octave Band Center Frequency [kHz]	Ceiling Values [dB]	Eight-hour Time Weighted Average [dB]
10	105	89
12.5	105	89
16	105	92
20	105	94
25	110	--
31.5	115	--
40	115	--
50	115	--
63	115	--
80	115	--
100	115	--

Infrasound constitutes acoustic emission below the audible range of human hearing. Infrasound in the crew compartment or habitat should be limited to 120 dB within the frequency range of 1 Hz to 16 Hz for a twenty-four hour exposure (NASA 1995).

2.4.2.5 Hazardous overall noise limits

Excessively loud overall noise levels can cause harm to the hearing of crewmembers, and should be limited. The noise level during flight in the integrated crew compartment or habitat is limited to a maximum of 85 dBA at the crewmembers' ears (NASA 1995). For sound levels of 85 dBA and above, hearing protection use is required for any duration of exposure. Noise from hardware associated with cabin depressurization, repressurization, or similar activities should be limited to

105 dBA at the crewmembers' ears during these types of operations (NASA 2006). For such activities, operational limits on noise exposure should be considered.

2.4.2.6 Reverberation time

Reverberation time, T60, is the time required for the energy density in an acoustic field to reduce to a level 60 dB below its steady state value, once the source is turned off. Reverberation time has a pronounced effect on speech intelligibility. Because it is an important criterion for conversational speech, the reverberation time should be adjusted to the volume of the crew compartment or habitat. For volumes the size of ISS modules, a T60 value of < 0.6 seconds is preferred (NASA STD 3001).

2.4.2.7 Alarm Audibility

Alarm signals used within the crew compartment or habitat must be clearly audible, and be easily discernible by crewmembers when working or sleeping. The "effective masked threshold" should be distinctly exceeded. "Effective masked threshold" is the level of alarm signal just audible over the ambient noise, taking into account the ambient noise in the habitat. If relevant, the probability of hearing loss in the recipient population may be assessed and taken into account. If hearing protection is worn, their levels of attenuation will be known and can be included in the assessment. The "upward spread of masking" effect should also be taken into account (ISO 2003). Signals from local loudspeakers or those that emanate from other locations within a spacecraft, *e.g.*, adjacent crew compartments or modules, should possess sufficient signal-to-noise ratio to be heard over the local background noise. To ensure alarm audibility, NASA space flight programs have adopted the criteria given in ISO 7731:2003, in that the sound-pressure level of the alarm signal at the location of the crewmembers' ears should meet at least one of the following criteria: 1. using measurements of A-weighted sound levels, the difference between the

two A-weighted sound-pressure levels of the signal and the ambient noise must be greater than 15 dBA; 2. using measurements of octave-band sound pressure levels, the sound pressure level of the signal in one or more octave-bands must exceed the effective masked threshold by at least 10 dB in the frequency range from 250 Hz – 4000Hz; 3. using measurements of 1/3 octave-band sound pressure levels, the sound pressure level of the signal in one or more 1/3 octave-bands must exceed the effective masked threshold by 13 dB in the frequency range from 250 Hz – 4000Hz. ISO 7731:2003 provides a method to be used to calculate the effective masked threshold to take into account the “upward spread of masking” effect, as well as examples for taking into account hearing loss and hearing protection use. If the alarm is to be used to wake sleeping crewmembers, then the first method, using a criteria of greater than 15 dBA signal-to-noise ratio between A-weighted sound levels of the signal and ambient noise (no masked threshold calculation needed), must be used. Finally, the maximum A-weighted sound level of the alarm signal is allowed to be 95 dBA or less at the crewmembers’ ears, since the alarm can be silenced.

2.4.2.8 Operational Requirements and Noise Exposure

Apart from the above acoustic design requirements, operational requirements and “flight rules” are also used to indicate when hearing protection is needed to protect the crewmembers from noise-induced hearing loss. For example, with the 24-hour, 7-day per week nature of spaceflight on ISS, a hearing conservation standard has been applied to a 16-hour crew work period, and an 8-hour sleep period, using a 3-dB equal energy exchange rate. According to the World Health Organization (WHO 1999), “hearing loss is not expected to occur at LAeq,8h levels of 75 dBA or lower, even for prolonged occupational noise exposures.” This level corresponds to an LAeq,16h of 72 dBA or lower using the internationally accepted 3-dB equal energy exchange rate. In addition the WHO states, “It is expected that environmental and leisure-time noise with an LAeq,24h of 70 dBA or lower will not cause hearing impairment in the large majority of people,

even after a lifetime exposure." This LAeq,24h level of 70 dBA corresponds to an LAeq,16h "work" level of 72 dBA and an LAeq,8h "sleep" level of 62 dBA using the 3-dB exchange rate. Combined, these are the 24-hour noise exposure limits applied to ISS crewmembers. The 85 dBA hazard level is applied here as a ceiling limit, where hearing protection use is required for any duration of exposure to sound levels of 85 dBA and higher, except for alarms which are subsequently silenced.

In order to assess the noise level and to take the necessary protective measures, a Noise Hazard Inventory (NHI) has been developed and provided to the ISS Mission to state when hearing protection is needed, according to the above flight rule. This NHI is based on noise exposure levels measured on the ISS or calculated from ground and on-orbit sound level meter measurements and corresponding exposure durations. On-Orbit Hearing Assessments (OOHAs) also are performed periodically, to detect the onset of any hearing loss so that countermeasures can be implemented in a timely fashion.

2.4.3 Compliance and verification

It is intended that acoustics design requirements and limits be met without the attenuation afforded by hearing protection, communication headsets, or other coverings, except during launch, entry, burn, or other short-term limited phases of a mission. An example of a limited phase would be that which occurs during cabin depressurization. Meeting the acoustics limits ensures a safe and habitable environment, and precludes the use of the hearing protection and other means noted from being imposed upon the crew and their subsequent reliance on it rather than using the actual design implementation for protection.

Frequently, acoustic requirements at the beginning of a program are challenged. They typically are regarded as too strict, and considered to lead to unacceptable impacts and expense. However, the previously discussed requirements and limits can be met if the appropriate resources and efforts, experience, and expertise are applied, especially if addressed early in the program at hand. Experience has shown that excessive exceedances of acoustic requirements can be very expensive to rectify late in the program both in terms of cost and schedule.

Verification, another key pillar to a good design, is a process that defines what needs to be completed and how this is to be done to prove that requirements have been met. It is usual practice to have companion verification procedures written by the originator of the requirements. These procedures ensure that every verification includes how to test, demonstrate, inspect, or analyze the system to show that the requirements have been satisfied. To be effective, the verification procedures need to be stated as precisely as possible, and as well should define the system test success criteria and the use of necessary equipment. Verification of sound pressure level requirements is recommended to be verified by test, although analysis and modeling is often used to make corrections to the test data that does not accurately represent the on-orbit or microgravity environment, e.g. as when vibration isolators are used in microgravity, or when a test of the complete system of hardware is not possible, e.g. as when evaluating noise from a payload that is being added to the currently orbiting ISS.

An acoustic noise control plan is required to define the basic efforts necessary to ensure compliance to the requirements. The noise control plan should include the selection or development of quiet noise sources, and the procedures employed to determine and control their levels. It should include methods of analyses or computer-based acoustic modeling for use to define allocated requirements, identify the primary propagation paths, and define noise control

treatments. As well, it should include plans for development and verification testing. The noise control plan should be updated throughout the life of the program to reflect completed and current status of efforts to implement it. By monitoring the progress of the noise control plan, and through oversight of the associated design and development efforts, an understanding and agreement with the efforts contribute to full compliance with the requirements. When requirements are not met, one aspect in a possible waiver or deviation assessment should be to address whether early and reasonable efforts towards compliance have been applied. If proper monitoring of the design and development process is performed, then reasonable efforts are addressed and attended to as early as possible in the program. Requirements might be perfectly written, but if they are not implemented and verified correctly, and with the right equipment, methods, and experience, then the purpose of the requirements cannot be achieved.

2.4.4 Conclusions and recommendations

Stringent acoustic requirements are considered necessary for current and future spaceflights for the protection of the safety and well-being of individual crewmembers, and for the successful completion of their intended missions. The acoustic requirements applicable to the habitable volume and other areas accessible to the crew, the integrated hardware, the supplementary government furnished equipment, and other payloads need to be defined early in the program cycle, be implemented correctly, and verified. The requirements are uniquely dependent upon the character, duration, frequency content, and level of the noise source emissions. A noise control plan strongly is recommended, and it should be updated throughout the design, the manufacturing stages, and all flight phases of the space vehicle. The noise control plan, in combination with monitoring and oversight of the design, development, and verification efforts, is essential to achieve full compliance with the defined acoustic requirements.

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Center.

Space Suit Acoustic Requirements

When wearing a spacesuit, crewmembers are exposed to the noise environment created by the spacesuit's life support system. For the most part, the noise comes from fans, pumps, and airflow. When the spacesuit is connected to the spacecraft for ventilation or water-cooling, noise can come through the umbilical connections or through the visor, if it is open. Inside the suit, the crewmember wears a communications headset for clear communications, so noise levels inside the suit must be controlled to reduce interference. Also, the background noise levels can be picked up by the communication system's microphone and interfere with the voice of the crewmember, trying to communicate to the ground or another location. For these critical communications, a speech intelligibility of 90% or higher word identification rate is desired. In order to achieve this, continuous sound pressure levels of background noise in the suit should be limited to NC~52, when the suit is at a pressure of 1 atmosphere (14.7 psi), or when the visor is open.

As the pressure inside the suit is reduced, as is typical during Extravehicular Activity (EVA), the noise levels in the suit will also be reduced because of the reduced air (or Oxygen) density. However, the output of the communications headset will also be reduced, and it will require more vocal effort to produce the same sound level of speech. These effects tend to counteract each other so that effective communications can be maintained. The suit's volume controls help to optimize the situation, and the communication system is designed to provide a sufficient sound level at the crewmember's ears to overcome background noise. However, the headset volume should be limited so the maximum sound level does not exceed 115 dBA at the highest suit pressure. The volume control can be used to reduce the intensity of the sound as needed by the crewmember. The 115 dBA sound level has been set as the ceiling limit by the U. S. Occupational Safety and Health Administration (OSHA) for permissible exposure.

Another important function of the spacesuit is to provide noise attenuation and hearing protection during launch, ascent, launch abort, descent, and landing of a space vehicle. Noise attenuation and hearing protection are also usually needed when activating pressure equalization valves, as when going EVA through an airlock. For these high noise events, it is recommended that the crewmember's noise exposure levels be controlled to an equivalent 85 dBA, 8-hour time-weighted average (TWA), using a 3 dB exchange rate. This is the National Institute of Occupational Safety and Health (NIOSH) recommended exposure level (REL) (NIOSH 1998). Remembering that a ceiling limit of 115 dBA is recommended for any sound level at the crewmember's ears, then to preserve 10 dB of headroom for communications and alarms, continuous background noise levels inside the suit at the crewmember's ears should be limited to 105 dBA. In cases where communications are not necessary, e.g. during launch-abort, the 115 dBA ceiling level can be used as the limit for the external noise at the crewmember's ears.

In order to determine the amount of attenuation (and hearing protection) needed from the suit, it is necessary to understand the noise environment in the crew cabin or habitat produced by these high level events. This environment is typically predicted, based on scale-model, wind tunnel, ground, or flight tests. For launch and abort noise, flight testing is the most accurate method for determining the crew cabin acoustic environment. For example, Figure A shows the Space Shuttle orbiter maximum external and internal noise levels (NASA 1995), measured during flight. Comparing the internal maximum sound level to the limit of 105 dBA, a suit attenuation allocation can be developed that will protect for adequate communications during launch. This attenuation allocation, usually expressed as ΔdB in each octave band frequency, can be readily verified by a ground test. Figure B, shows the STS-3 Shuttle orbiter Flight Deck (internal) A-weighted sound levels as a function of time after launch. This data, once adjusted to take into

account spacesuit attenuation and communication system hearing protection, can be used to compare against the REL noise exposure requirement discussed above.

One further note on the noise exposure requirement, for these suited noise exposures that are rare in occurrence, the NIOSH 85 dBA 8-hour TWA REL is used. This REL allows an 8% excess risk of developing a noise-induced hearing loss after a 40-year lifetime exposure (NIOSH 1998). This risk should be further reduced with the limited number of exposures of these types of events. For 24-hour, 7 days per week long-term noise exposure, as on ISS, the more conservative World Health Organization (WHO) noise exposure limit of 75 dBA for 8-hour TWA exposures are used to reduce the crewmembers' risk for hearing loss.

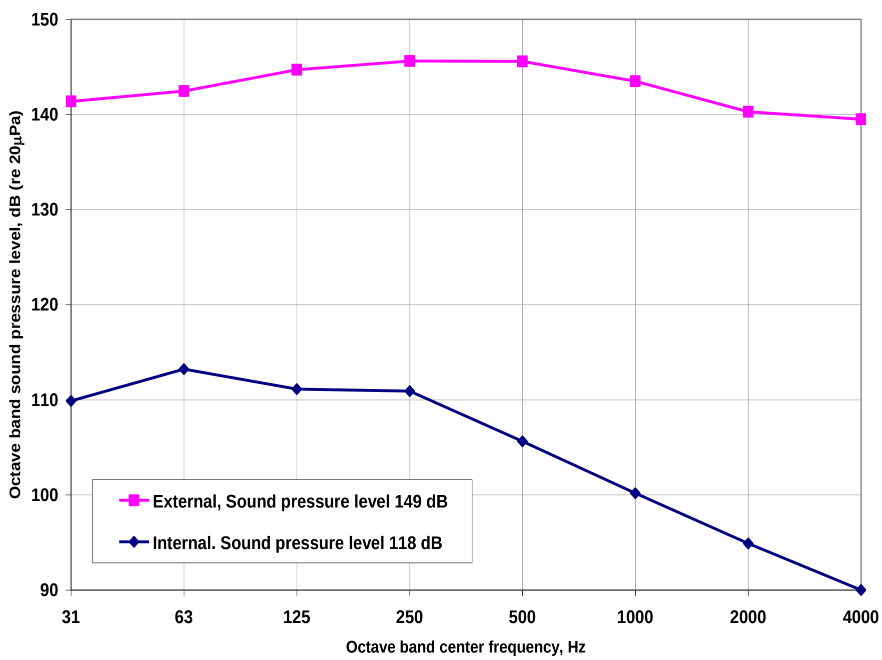

Figure A. Measured Space Shuttle orbiter crew module maximum noise during launch phase (NASA-STD-3000, 1995).

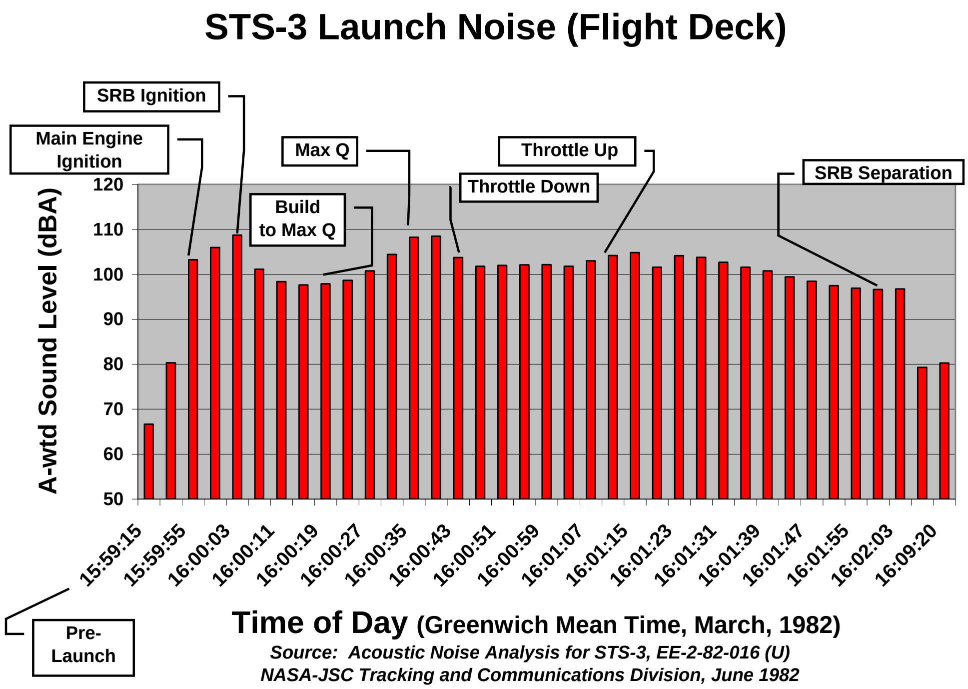

Figure B. Space Shuttle orbiter internal noise. Noise in the flight deck during the atmospheric launch phase as a function of time, analyzed using a 4-second time window (Nealis, 1982).

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